The Intel 4004 Microprocessor: What Constituted Invention?

WILLIAM ASPRAY

This paper investigates the context for the development of one of the earliest microprocessors, the Intel 4004. It considers the contributions Intel employees, most notably Marcian E. "Ted" Hoff, Jr., and Federico Faggin, made and contributions other people made to this development who are not generally known, most notably Tadashi Sasaki and Masatoshi Shima. The paper represents a case study of how corporate and national cultures affect technological development and of the many aspects of invention, including conceptualization, logical design, engineering, fabrication, capitalization, and marketing.

Introduction

The microprocessor is among the most ubiquitous and powerful technologies of the late 20th century. It is not surprising, then, that credit for this invention has been widely discussed—especially in the past several years, since an obscure inventor named Gilbert Hyatt was awarded a U.S. patent, to the consternation of the semiconductor industry.[1] With many inventions, there is a tendency, after their significance becomes widely appreciated, to reconstruct the history, making the story simpler, more rational, and more heroic. This is the case with the microprocessor, which is widely credited to the engineering genius of Marcian "Ted" Hoff at Intel.[2]

It is not my intention to disparage the accomplishments of either Hoff or Intel. Hoff is a gifted and accomplished engineer who played a fundamental role in the development of Intel's first microprocessor, the 4004; and Intel has repeatedly demonstrated its capabilities while becoming a dominant force in the global semiconductor industry. But the story of the invention and development of the microprocessor is not as simple or straightforward as is generally told.

This paper aims to tell a more interesting and complex story by examining the historical context in which the 4004 was developed, both outside and inside Intel.[3] I will show, for example:

- that the conceptualization of the microprocessor, which was Hoff's principal contribution to the 4004 project, was independently conceived in other companies and Hoff was aware of some of this work;
- that Hoff had a relatively minor role in the hard work of making the 4004 a commercial reality (i.e., the detailed logical design, engineering, applications development, and marketing);
- that the stimulus and financing for the 4004 project came from a Japanese company, not from Intel; and
- that Intel did not originally embrace the microprocessor as an important part of its product line.

By considering corporate and even national cultures, we can gain a new and deeper perspective on this important invention.

Background

During the 1950s, the basic control element in computers, widely known as the logic gate or switch, was implemented using vacuum tubes or discrete transistors. Integrated circuit technology, using layers of metal and oxide on a polished silicon chip, began to be used to implement logic components for computers, replacing transistors, diodes, and resistors on printed circuit boards. In the early 1960s, the scale of integration, a measure of the number of logic components that could be placed on a chip, was a few dozen; and chips were used mainly to implement individual logic devices. By the mid-1960s, with continuing improvements in the semiconductor field—mainly, better etching and manufacturing techniques and improved circuit design—more functionally complex logic devices such as adders and shifters could be implemented on a chip. The scale of integration continued to rise rapidly, approximately doubling every year. By the mid-to-late 1960s, it was practical to begin considering semiconductor devices to replace magnetic cores as the primary storage device for mainframe computers.

Technological conditions were favorable for the development of the microprocessor in the mid-to-late 1960s. The increase in scale of integration made it possible to place ever more elements of a computer circuit onto a single chip, leading engineers to speculate about building a computer on a chip. Federico Faggin, who led the engineering work on the 4004 project at Intel, acknowledged this fact:

> By the mid-1960s people were building single-board microcomputers, using MSI [medium-scale integration] as a side function. It didn't take geniuses to figure out that this pattern of continuing integration and combining functions was going to happen. To people in the art and inside the industry, it was the natural thing to do. The question was, "When will we have the technology that will allow it economically?"[4]

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In an interview with the author, Hoff indicated that, at the time he conceived the microprocessor that became the Intel 4004, he was aware of similar ideas engineers had expressed at several other organizations, including SRI, IBM, and RCA.[5] Additional work was being conducted at Fairchild, Rockwell, General Instruments, and Texas Instruments at about the same time, although there is no reason to believe that Hoff was aware of it.[6] As I shall show in the next section, a similar idea had also been discussed at the Sharp Corporation in Japan.

The economic climate was also favorable to the development of the microprocessor. In a thoughtful and widely read review article, Hoff and Intel President Robert Noyce made this case:

> By the late 1960s, the semiconductor industry was becoming aware of a serious design problem. The complexity of random logic designs was increasing steadily. If this continued, the number of circuits needed would proliferate beyond the available supply of circuit designers. At the same time, the relative usage of each circuit would fall. IC [integrated circuit] cost effectiveness would suffer; increased design cost and diminished usage would prevent manufacturers from amortizing costs over a large user population and would cut off the advantages of the learning curve.[7]

Hoff and Noyce went on to argue that "the microprocessor was a very necessary invention—and that its rapid acceptance was in many ways predetermined."[8] This article disputes their claim for autonomous technological development. Technological and economic forces set a context for the development of the microprocessor, but it was human choices by the semiconductor manufacturers, systems manufacturers, users, and perhaps others that shaped the technology. In fact, on the same page as their assertion about the necessity of the microprocessor, Hoff and Noyce suggest some of the alternative approaches that might have been taken to solve this technicoeconomic problem, such as computer-aided design, discretionary wiring, and master slicing.

Tadashi Sasaki and the Early Japanese Semiconductor Industry

Although it is little known outside Japan, one important line in the story of the microprocessor's development began with electrical engineer Tadashi Sasaki.[9] Because Sasaki is not widely known in the West, I will take some space to detail his career. He was born in 1915 in Taiwan but grew up in Japan. In 1938, he graduated from Kyoto University with a distinguished record and a bachelor's degree in electrical engineering. He worked for a short time on circuit design at the Electrotechnical Laboratory—a preeminent research laboratory sponsored by the Ministry of Telecommunications—before moving to the aircraft manufacturer Kawanishi Kogyo, which was integrated into Kobe Kogyo after World War II and absorbed by Fujitsu in 1963. Sasaki worked on antiradar devices during World War II for Kobe Kogyo's vacuum tube division. Dr. Sasaki, who received his PhD in electrical engineering from Kyoto University in 1961, remained with Fujitsu until 1964, serving in research and management positions of increasing responsibility.

During his years with Kobe Kogyo, Sasaki was a leader in establishing the Japanese semiconductor industry. He met John Bardeen on a tour of Bell Laboratories in 1946. During 1947, just before Bardeen and his coworkers invented the transistor, Sasaki had several communications with Bardeen about the limits of miniaturizing vacuum tubes. As Sasaki explained it, while he worked to make the distance between the grid and the cathode progressively smaller, Bardeen made the conceptual leap to embed the grid in the cathode, which resulted in the point-contact transistor. Bardeen personally sent Sasaki news of his invention within a few weeks after it occurred. Sasaki recognized the significance of Bardeen's contribution and promptly initiated a research program at Kobe Kogyo on transistors, later supported by the Ministry of International Trade and Industry. Leo Esaki, who won the 1973 Nobel Prize in physics for his research on semiconductors, was the first researcher to work on transistors under Sasaki's direction. Sasaki's interest in semiconductors has continued up to today.

Bardeen made the conceptual leap to embed the grid in the cathode, which resulted in the point-contact transistor.

In 1962, the British company Sumlock Computer began manufacturing a desktop calculator, known as the Comptometer Mark IV, which became a major commercial success in Japan. Japanese companies were struggling to make calculators using vacuum tube components, and, spurred by this foreign threat, Sasaki sought to replace vacuum tube components in Japanese calculators with transistors. At the time, Kobe Kogyo was supplying electronic components to Sharp Corporation, a leading manufacturer of domestic appliances. Sasaki persuaded Sharp, which had no experience in the calculator business, to send several of its young engineers back to the university for additional training in computing as a first step toward entering the semiconductor-driven calculator business.

Because of management restructuring within Fujitsu, Sasaki decided to leave for a senior management position at Sharp in 1964. His arrival at Sharp coincided with the return of the engineers from the university where they had received their extra computer training. Unlike Kobe Kogyo, Sharp was in a financial position to provide adequate development funds, and Sasaki was able to put the engineering staff to work developing semiconductor-based calculator products. He believed that if he could replace the large mechanical calculators then in common usage with smaller electronic ones, the new calculators might find a market in the home and build on Sharp's experience in domestic electrical appliances. Under Sasaki's sponsorship, Sharp soon produced the world's first transistorized calculator.

Sasaki closely monitored the U.S. semiconductor industry, with the intention of serving both his own company and the entire Japanese electronics industry. He observed the U.S. move from small- to medium-scale integration and persuaded several of his Japanese colleagues to follow suit. He argued, with less success, for the move from bipolar to majority-carrier devices. In what seems to be a characteristically Japanese management style, Sasaki used analogy to explain and partly justify his preference for single-carrier devices:

At the time the Sharp Corporation hired many, many young girls for the assembly operation, for production. Sharp Corporation had built many dormitories for several-person occupancy. They also built housing complexes for married couples. Then I realized that what is more efficient and cost effective is singles' dormitories: they are much better than the couples' dormitory because in the case of the singles' dormitory, you don't have to think up any design. It's very simple, and you don't have to worry about any separations between them. Then I put that idea into semiconductor devices. People have used the p-n junction, and they had to put some insulator with it. It's no good for the future miniaturization of devices. So I recommended utilizing the single type of transistor structure without insulator.[10]

In 1966, Sharp began work on *p*-channel MOS technology, which it learned about from a technical report prepared by Fairchild Semiconductor. Two years later, Sasaki began to worry that calculators built with *p*-channel MOS technology would consume too much power for battery operation and would operate too slowly, so he introduced work on complementary metal-oxide semiconductor technology in his company. However, this created a new problem: Too great a percentage of the power was being consumed by the display unit. In response, he initiated what turned out to be one of the first and most successful research programs in liquid crystal displays.

Sasaki's role in the development of the microprocessor came about as part of his effort to keep Sharp at the forefront of the Japanese calculator business. During the mid-1960s, every two years the number of chips required to make a calculator was halved because of the rapid pace at which the semiconductor scale of integration was progressing. As a result, Sharp anticipated product life cycles for calculators of two years or less. By 1968, some calculators were being built from as few as four chips. Projecting a continuation of this trend, Sasaki organized a series of brainstorming sessions with about 10 of his engineers and circuit designers to plan for the future generations of calculators.

Most of the engineers suggested an incremental increase in the overall functionality of the calculators by taking advantage of the increasing scale of integration to continue to put more on each chip. Sasaki rejected this idea as simply the kind of conservative thinking that is ingrained by the Japanese university system—to make incremental extensions rather than technological leaps. However, one member of the team, Ms. Murakami, who was a software engineering researcher who had recently graduated from Otani University in Kyoto, focused instead on increasing the functionality of individual chips. Noting the reduction in the number of chips needed to build a calculator over the previous several years, she suggested that if the trend continued, the number needed would decrease to two, then one, then a fractional number.

What she meant by a fractional number is not entirely clear, but it seems she meant that the calculator comprised multiple functional units and that one could divide a chip into multiple regions, placing in each region a complete functional unit, with buffers to bypass. This leads one to emphasize the implementation of an entire functional unit, such as a central processing unit, on a single chip (or portion thereof). Thus, while the other Sharp engineers focused on the functionality of the calculator, Murakami focused on the functionality of the chip. Sasaki liked her suggestion, but the other engineers did not find particular value in it. Sasaki made his decision on the future research direction in a customary Japanese way, on the basis of the majority opinion, which he later acknowledged to be a mistake. He did arrange for the company's shops to experiment with a program he called Components on Silicon, but the major thrust of research was along the lines of the majority opinion, without any particular effort to build a complete central processing unit on a chip.

However, Sasaki would not readily let go of the idea of the fractional chip. The U.S. manufacturer Rockwell had an exclusive contract to supply the semiconductor devices Sharp used in its appliances. Sharp was an important customer to Rockwell, and there were mature working relations between them. Sasaki asked Rockwell to produce these four-division chips, but Rockwell refused—according to Sasaki because Rockwell was already earning high profits with its other semiconductor devices and did not want this distraction.

Thus, while the other Sharp engineers focused on the functionality of the calculator, Murakami focused on the functionality of the chip.

In 1968, in the first several months after Intel was founded, Noyce visited Sasaki at the Sharp offices in Nara, Japan, hoping to sell Intel's manufacturing semiconductor devices to Sharp. Sasaki felt beholden to Noyce because of the important use he had made of Noyce's earlier results at Fairchild on planar-type semiconductor devices; so he asked Rockwell if it would allow Intel, a new and struggling firm, to produce a small percentage of Sharp's semiconductors. Rockwell refused, pointing to its exclusivity agreement with Sharp.

At that point, Sasaki decided to take entrepreneurial action behind the scenes. Yoshio Kojima was the president of a young and unproven calculator company named Busicom, short for Business Computer, that was experiencing some financial problems. He and Sasaki had graduated from the same university department (although at different times), and university ties being strong in Japan, Sasaki did not want to see Kojima's business fail. Sasaki had previously given technical advice to Busicom, which is permissible in Japanese business culture since Busicom was small and posed no serious threat to Sharp. Thus he decided surreptitiously to provide 40 million yen to Kojima, with the stipulation that Busicom would front a contract with Intel to manufacture the four-division chip. This funding was used to pay for the development contract with Intel that led to the development of the 4004 microprocessor.

Masatoshi Shima and Busicom

At this point, the story shifts to Busicom and a young engineer employed there named Masatoshi Shima (Fig. 1). In 1967, Busicom was manufacturing mechanical and electronic desktop business calculators, selling Mitsubishi mainframe computers, developing operating systems and applications software for Mitsubishi, and importing business computers from France. Busicom calculators (Fig. 2) were sold in the United States under NCR's trade name and were also exported to Europe and other parts of Asia.

Shima, who was born in Shizuoka, Japan, in 1943, graduated with a major in organic chemistry from Tohhoku University in 1967. That year, there was a downturn in the chemical industry. Not able to find a good job as a chemist or chemical engineer, he accepted a position as a software engineer at Busicom. Computers were just beginning to be used in Japan in the chemical analysis of organic compounds when he went to college, and hoping for a career in scientific programming, he joined Busicom.

Some of Shima's first work at Busicom involved programming the Mitsubishi MELCOM 3000 computer, even though he had never had any formal training in either computers or electronics. However, he did not find sufficient challenge in the programming tasks assigned to him, especially since most were business rather than scientific applications. Busicom had a factory in Osaka, Japan, that manufactured electric desktop calculators, and he was granted permission to transfer there to work as a hardware engineer after completion of six months of employment with the company. He had no training in hardware engineering either, but he taught himself some rudimentary electronics by reading textbooks and attending a one-month course on automation.

Fig. 1. Masatoshi Shima.

Photo courtesy of M. Shima.

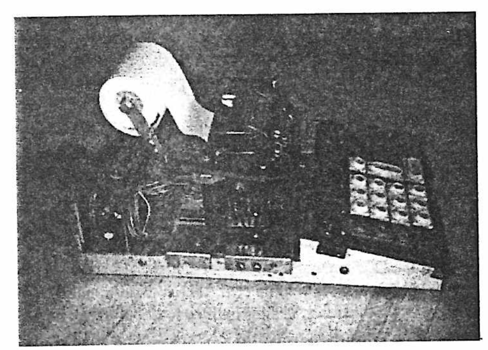

Fig. 2. A Busicom calculator.

Shima was fortunate in that he joined the company when it was moving from using discrete transistors to integrated circuits in its desktop calculators. He soon discovered that he did not have to learn as much about the physical properties of transistors as about the logical design of the calculator as a system (main processor, memories, display, keyboard, and other peripherals) and about the architecture of integrated circuits. Thus he found he was not particularly handicapped by his lack of traditional grounding in electrical engineering.

The Japanese calculator industry was then undergoing rapid transformation, driven by the rapid innovations in the microelectronics components used in calculators.[11] A particularly landmark event was Seiko's introduction of a fast, compact impact line printer for the 1964 Tokyo Olympics, which all the Japanese calculator manufacturers wanted to incorporate in their products. By this time, virtually all calculators were being made in Japan. U.S. and European firms had dominated the mechanical and electromechanical calculator businesses earlier in the century, but they had been slow to make their products electronic, and market share had shifted rapidly to Japan. Only one U.S. company, Monroe, was still manufacturing calculators.

Busicom was not immune to these competitive forces. Tadashi Tanba, Shima's supervisor in Osaka, had used a hardwired approach—the way in which calculators had traditionally been designed —to design several calculators for Busicom. But because of the competitive pressures for more rapid product development, Tanba decided to draw on his experience in the computer industry, as an engineer for Control Data Corporation, to design a calculator using a programmed approach, blending computer software technology with desktop calculator hardware. He believed this would allow changes to be incorporated into the product line more rapidly. He assigned Shima to this project because of his programming experience. This occurred in 1968, about one year after Shima joined Busicom.

During 1968 and 1969, using a program logic method instead of hardwired logic, Shima developed the Model 141-PF, a desktop calculator with printer that Busicom produced and sold successfully for small-business applications. Consciously mimicking the design of the main block of a computer, Shima incorporated in his calculator design read-only memory, entry registers, accumulation registers, multiplication registers, and two arithmetic units (adders). He also defined and designed the macro-instruction set for the calculator, based on what was being used in decimal computers. All of this work was done, he claims, in complete isolation from people outside his small development group in Osaka.

A new business challenge to Busicom came in late 1968, when Sharp, with assistance from its U.S. partner Rockwell, introduced a desktop calculator using large-scale integration (LSI) to squeeze the 200 or so basic components in a calculator onto only four chips. The competition was surprised that Sharp could achieve a design with so few chips.

Busicom's response was two-fold. It began to develop its own LSI-based calculator line and seek out U.S. semiconductor companies that could be its partner in the same way that Rockwell aided Sharp by preparing logic schematics and circuit designs for chips to be used in the calculators. Busicom had two factories manufacturing calculators—Osaka's Nippon Calculator Machine Corporation, manufacturing small-business machines in high volume, and Tokyo's Electro Technical Industries Corporation, manufacturing scientific calculators and specialized office equipment such as billing machines and teller machines. The company

sought a basic LSI design that could be used across the entire range of products at both factories.

This technical objective was partly achieved. In the end, following the recommendation of a U.S. consulting firm, Busicom settled on two U.S. semiconductor partners, Mostek and Intel, and two design strategies. Mostek was contracted to provide the LSI technology for the small-business calculators built in Osaka. Intel was contracted to provide the integrated circuits for the products manufactured in the Tokyo factory. Sharp's small-business calculator with four chips had been implemented in metal-gate technology, so Busicom chose silicon-gate technology, which had the prospect of providing higher-scale integration than Sharp's approach—which was important since Busicom did not want to build simple calculators like Sharp was building for the home market but more powerful calculating machines for professional use. Mostek and Intel were chosen because they were the two U.S. semiconductor manufacturers that worked with silicon-gate technology and were not already aligned in business relationships with other Japanese calculator manufacturers.

The Osaka factory brought to Mostek the logic and circuit schematics, and Mostek manufactured the chips to Busicom's specifications. These calculators were first produced using two chips, but in 1970 Busicom was able to introduce a desktop calculator using a single LSI Mostek chip and hardwired random logic. The collaboration with Intel was not as straightforward.

Busicom and Intel: Defining a Product

The history of Intel is well-known and need only be summarized here.[13] Intel was one of the so-called Fairchildren, the companies started by former employees of Fairchild Semiconductor. It was incorporated in July 1968, after Noyce and Gordon Moore left Fairchild to exploit the commercial opportunities of the emerging LSI technology. Intel's primary goal was to produce a semiconductor computer memory to replace magnetic cores. The company's first big success came in late 1970, when it introduced the 1103, with one-kilobit dynamic random-access memory. By 1972, this product was replacing core memories in large numbers and was the most successful semiconductor memory on the market. Already, Intel was supplying memory chips to 15 of the 18 largest computer manufacturers.

When Busicom first contacted Intel about developing the chip set for its new line of computers, Intel was less than a year old. Despite the fact that Busicom's project was outside of Intel's major line of business in semiconductor memories, Intel welcomed the business, both to build up its client list and to provide it with some contract work to ease its cash-flow problems while it developed its proprietary memory chips. As Hoff explained:

> I was involved in some of [the contract negotiations with Busicom].... Most of Intel's other products were proprietary with the potential for fairly long design cycles. When you develop a new memory chip of your own design, you finally announce it to the world, and then you sit back for a year or two and wait for people to design it [into their products] and get their production going.... You are ready to make them by the millions and people are just buying them by the ones and twos to try them out. So the business of trying to get around that is doing custom silicon. When you do custom silicon, you are working with a design team that you hope is ready to run as soon as you are. Having something like that you hope will get around that cash flow problem.[15]

In June 1969, Busicom sent three employees to Intel's offices in Santa Clara, California, to describe the work they wanted done: project manager Mr. Masuda, senior engineer Mr. Takayama, and Shima, who was the junior member of the team but who nevertheless made the presentation. The contract task Shima outlined was to design a set of chips using LSI technology to run a family of high-performance programmable calculators. Read-only memory chips were to be added to customize the basic design for each model in the family. The meeting was followed on 16 Sept. 1969 by a letter presenting a formal offer of contract.

Intel originally gave responsibility for the Busicom project to Ted Hoff (Fig. 3), manager of the Application Research Department, with assistance from another engineer, Stanley Mazor (Fig. 4). Hoff had a strong technical background: an undergraduate degree in electrical engineering from Rensselaer Polytechnic University in 1958, a PhD from Stanford University in adaptive systems (what we would now call neural networks) in 1962, and six years' further experience at Stanford as a researcher, continuing his work on adaptive systems. He had joined Intel in 1968 and already completed some important work for the company on metal-oxide semiconductor (MOS) random-access memory before this assignment, which he received because of his systems and applications experience, even though by his own admission he was not a chip designer.[14]

Fig. 3. Marcian E. "Ted" Hoff, Jr.

Despite the value of the collaboration to both companies, the project did not progress smoothly during the first year. The Japanese team had already gone a long way toward completion of its design, having the logic schematics 80 percent to 90 percent complete in Shima's estimation.[15] They expected, not unreasonably, that with all of this work completed, the chip set could be produced rapidly. Shima was at first optimistic about the collaboration, but his confidence soon faded.

> [Hoff] had good abilities in many, many areas, including computers, software, circuit design, logic design, and simulation. In the beginning of the meeting[s] we thought that once we showed the logic schematic to them, they could understand what we wanted to do. But after several meetings, we found out that they didn't have a logic engineer to understand our logic schematics and they didn't have any circuit engineer to convert our logic schematics to circuit schematics....
>
> Also they didn't know about desktop calculators themselves. For example, Seiko's printer was a line printer unlike the slower serial printers they were familiar with [from Monroe calculators].... Therefore, we had to explain what these desktop calculators were, what the line printers are, and how to control them. After a couple of months of discussion, we were not able to reach agreement. Also, we had to explain the function and control of the keyboard, display, and card reader. It was quite a difficult job for us to explain because they had never seen them.
>
> Ted Hoff asked me many questions. I brought some other things. For example, ... the flow chart for the desktop calculator's program. Many times I explained the desktop calculator's program and the macro instruction set. He had a lot of questions about this flow chart, then he asked me, "Why don't you explain the instruction set?" I explained the list of instructions for the desktop calculator, showing the hardware block diagrams and flow charts and program ... based on the macro-level decimal instructions.[16]

Fig. 4. Stanley Mazor.

Hoff, however, had a different perspective. He regarded the Busicom design as too complicated and too expensive to implement, if one wanted to sell the calculators at a marketable price. He had been working with a Digital Equipment Corporation PDP-8 computer in his research and was struck by the difference between the PDP-8's lean architecture and the relatively complicated program logic in the Busicom design. He felt, in the Japanese design, "that hierarchical structure [of using a building block and over] seemed to be lacking."[17] (In particular, Hoff was concerned that the control logic for the various peripherals was done by separate structures; the shift register memory required complex timing; and the elemental instructions were intricate.[18]) The PDP-8 achieved its considerable power by making the design trade-off of employing a spartan instruction set but at the cost of a large program memory. Hoff saw an opportunity to take advantage of Intel's strength in low-cost semiconductor memories to make the same design trade-off in the Busicom design. He believed this approach had other advantages, only some of which were of importance to Busicom, which restricted its business interests to calculators:

> Reducing complexity of the elemental instructions could also make the resultant processor a more general-purpose machine. In the calculator, a program stored in ROM could utilize sequences of more general instructions not only for arithmetic, but for keyboard scan and debounce, display maintenance, and other functions as well. With the flexibility, Hoff thought, a more general-purpose processor might find applications quite apart from calculators.[19]

In August 1969, Hoff proposed to Intel management this approach of building a calculator by making a computer that was programmed to act like a calculator. Intel management endorsed the idea, and Hoff began to develop it.[20] Intel management was relieved not to have to design a larger chip set, such as Busicom proposed, because it would have taxed Intel's small staff.[21] In a later interview, Noyce corroborated and commented on this point:

> And it was a little difficult because we had at the time four or five circuit designers. We didn't have the spare resources to apply to this project, which was good because then that led Ted Hoff to the idea of trying to simplify this whole thing by finding an easier design path to their needs, and their objectives. It's the old story: necessity's the mother of invention. I can't do what you're asking me to do, so I've got to figure out a simpler way to do it, and of course that was the origin of the idea of having a programmable unit there, which is really the essence of the microcomputer: do the design job, have it programmable so that you can use it in the many, many different applications.
>
> There was discussion prior to that of the number of new designs that you'd have to do everyday in order to realize the potential of large-scale integration. I recall a discussion some years earlier at Fairchild, trying to extrapolate and guess what the world would look like if large-scale integrated circuits came in to effect, and basically what you're saying is we would have to design 10 circuits a day. This was at a time when designing a circuit took a year and the question [was] how you would ever accomplish that. The answer, of course, is you don't; you find another way around it.[22]

However, Shima was not convinced: "The basic idea from Ted Hoff was quite nice. But to use his idea for my applications, the detail was not so good ... lack of system concept, lack of decimal operations, lack of interface to the keyboard, lack of real-time control, and so on."[23] Shima had other problems with Hoff's approach as well. It required using the older transistor-transistor logic technology for system interface, whereas Busicom had approached Intel in the first place with the hope of avoiding all use of transistor-transistor logics, replacing them with the LSI components that were supposed to be Intel's expertise. Shima was concerned about the great expense for the extra read-only memory Hoff's design required. He was also frustrated that Hoff did not work out the details of his implementation.

From August to October 1969, Hoff pursued his approach, while Shima worked (also on-site at Intel) to improve and complete his original design. As Hoff remembers the situation:

> [The Japanese engineers, Shima in particular] had a great reluctance to change the design. I can understand it: they had a big investment. They had already done a fair amount of coding, so it would be very reasonable that he would not want to. At a conference a few years later, Shima said, "I had to write all my code over again!" The interaction was that I was going in one direction [and the Japanese in another]. Basically they already had a design that was pretty well along. As we explained what we felt some of the problems with their design were, they felt that they really did understand those problems and accepted them ... but they felt they could stay with the spirit of the original design ... to the logic, and doing so they were cutting the number of transistors and the number of chips necessary [thus addressing Hoff's concern that the implementation of the Busicom design would be too expensive].[24]

In October 1969, Busicom executives visited Intel, and the two approaches were described to them. Hoff presented a set of four chips: a two-kilobit read-only memory to store the program instructions (known as the 4001), a 320-bit random-access memory to store data (the 4002), a 10-bit shift register (the 4003), and a four-bit central processing unit (the 4004). All of these were on chips with 16- or 18-pin packages, which was the standard in the semiconductor industry (unlike the packages that Shima designed with larger numbers of pins, which were technically better but did not conform with industry standards—in fact, Shima did not know enough about the semiconductor industry to know that there were standard packages). The 4004 microprocessor, which was the most complex of the four chips, as proposed involved integrating an estimated 1,900 transistors on a chip.[25] Shima had reduced his design somewhat, but it still required 12 chips, averaging more than 2,000 transistors apiece, using nonstandard 36- or 40-pin packages. Although these comparisons seem to favor Hoff's approach, Hoff was surprised at the decision: "I always thought it was a coup that we managed to persuade the Japanese managers to choose our design over [the one of their own engineers]."[26]

Implementation and Marketing

Shima accepted the decision gracefully and began to work with Mazor to solve what he regarded as the shortcomings of Hoff's design. This work was completed by the end of 1969, and Shima returned to Japan in December to finalize the programming and documentation.[27] Over the next several months, he worked on some of the programming detail, a product manual, product specification, and some of the hardware architecture.

By the end of March 1970, Shima had completed this work and returned to California in April to see how Intel was progressing at turning the architectural design into silicon products, as well as to finalize the last few details in the contract between Intel and Busicom. He was distressed to learn that virtually no progress was being made. This delay at Intel seriously undermined Busicom's schedule to build its calculator line and jeopardized its market competitiveness.

> I visited Intel once again. That time I was told from Busicom that my main job was just to check what Intel was doing.... When I went to Intel, I found out they had not done anything! ... We fought it quite strongly because Busicom paid money and Busicom sent all the documents on each LSI product.... And at that time when I went to Intel, nothing was done. I was mad![28]

Intel management had pulled Hoff from the project to work on another contract, to develop a chip to serve as the central processor for an intelligent computer terminal (the Datapoint 2200) for Computer Terminal Corporation—a project that ultimately resulted in another, but more powerful microprocessor known as the 8008. (Shima was not informed of the fact that Hoff had transferred to another project until he arrived in the United States in April 1970. He took out his anger on the project's new chip designer, Faggin, until he learned that Faggin had joined Intel only one week before and did not even know any of the details of the project yet.)

Intel did not regard the Busicom contract as a high priority and did not then see a place for the microprocessor in Intel's future.

Hoff's redeployment was a reasonable management decision for Intel. Hoff was manager of the Applications Research Department and was skilled at the applications aspects of the development process but not in the details of chip layout and fabrication. When Hoff was reassigned, the setting of the design in silicon for Busicom was turned over to Les Vadasz, head of Intel's MOS design team. However, this created several problems. Vadasz and his staff were too preoccupied with Intel's principal business, the design of memory chips, to do much work on the Busicom chip set; moreover, their experience was in memory chip rather than logic chip design. It was clear they needed to hire someone with appropriate experience to carry out the Busicom project, but it took them six months to do so. Partly it was because there was a shortage of qualified chip designers available for hire; apparently it was also partly because Vadasz was reluctant to hire the most qualified available person, Faggin, because of the friction between them when they had worked together at Fairchild.[29] Another reason may have been that Intel did not regard the Busicom contract as a high priority and did not then see a place for the microprocessor in Intel's future.

Eventually, Intel did hire Faggin (Fig. 5), who proved to be an excellent choice for the next stage of the project. He had received a PhD in physics in 1965 from the University of Padua.[30] He lectured in physics for a year at the university before holding positions in several Italian companies, where he helped develop an early process technology for MOS devices. He came on exchange to Fairchild in the United States in 1968, where he played a major role in developing new silicon-gate technology for fabricating high-performance, high-density MOS integrated circuits.

Intel hired Faggin in April 1970 expressly to work on the Busicom project, with the understanding that the architecture and logic design were already completed and only some circuit design and the chip layouts remained to be done. However, he found the project much less advanced than he had been led to believe: Many architectural and logical design issues were unresolved, and he found the Intel staff to be little help in resolving these matters.

With some assistance from Shima and Mazor, Faggin worked furiously for the next year on the project, often putting in 12- and 16-hour days. He has indicated that "I wanted so badly to do a good job that I almost worked myself to death to meet the schedule."[31] He resolved the remaining architectural problems, prepared the final logic and circuit designs, and developed a new process for laying out the four chips. The 4001 (read-only memory) was completed in October 1970 and the 4002 (random-access memory) and 4003 (shift register) the following month—with very few flaws appearing. There were minor problems with the 4004 (central processing unit), and the masks were not perfected until February 1971. By March, full chip sets were sent to Busicom for testing—a set consisting of four 4001s, two 4002s, two 4003s, and one 4004. The speed at which Faggin was able to complete his work and the high quality of the results he produced are great testaments to his ability and effort.

Fig. 5. Federico Faggin.

Shima remained at Intel from April until November 1970. During this time, he worked on a detailed logic schematic that he believes to have been instrumental in the chip layout. He also worked on logic simulation and on a test program, which was used to verify that the set worked properly.[32] Between April and October, Shima's colleague, Masuda, developed a breadboard of the calculator based on the logic schematic that Shima had prepared while at Intel. In December 1970 and January 1971, Shima used this breadboard to build a prototype of the printer desktop calculator. In March 1971, he was able to rebuild the prototype into a fully functional model using a 4004 chip made at Intel (see Table 1).[33]

Starting in April, Busicom began the manufacture of calculators, billing machines, cash registers, and teller machines based on the new technology. Most of these machines were manufactured on an original equipment manufacturer basis, with NCR as the main customer. Sales reached 100,000 units.[34] Busicom made some use of the flexibility of the microprocessor approach by using microprogramming to introduce new features into several of the calculator models—a flexibility that customers apparently appreciated.[35] But Hoff has argued that the microprocessor design did not have major importance to Busicom:

> Probably [the general-purpose capability of the microprocessor had] not that much [economic value to Busicom]. ... The only advantage [in the calculator business] was in a smaller number of designs, higher volume and lower cost of production, getting down the learning curve faster. [On the other hand] there is no guarantee that the original [Busicom] design would have been any better, and maybe it would have been a lot worse.[36]

TABLE 1
THE 4004 MICROPROCESSOR

The 4004 was a four-bit microprocessor, measuring 0.11 × 0.15 inch and containing 2,300 MOS transistors. It incorporated a four-bit adder for doing additions, an accumulator for keeping track of partial sums, and 16 registers for temporary storage. The 4004 could perform 60,000 executions a second and address 1,280 half-bytes of data and 4K bytes of programmed instruction. Two four-bit numbers could be added in about 11 millionths of a second.
Gathered from S. Augarten, *State of the Art*. New Haven, Conn., and New York: Ticknor and Fields, 1983.

More interesting is the fate of the microprocessor at Intel. During the development of the chip set, Faggin had felt that he always had to struggle for resources:

> One possible reason for having to fight for those resources is that there was a lack of understanding at a more senior management level. Possibly the company just didn't have the resources to give. Maybe this project was not considered as important as the memory chips they were working on.[37]

There was a recession in 1970, chip orders had not increased as rapidly as Intel had expected, and Intel was strapped for cash. The company laid off workers and delayed moving into its new headquarters building. Memory, rather than logic chips, remained the company's main interest. In any event, under the terms of the contract, Intel could manufacture only the chip set, including the 4004 microprocessor, for Busicom's use; there was no opportunity at this time for Intel to build a business manufacturing and selling microprocessors.

The situation changed rapidly, however. Other Japanese manufacturers were producing calculators in high volume, and Busicom felt that it had to lower its calculators' prices in order to remain competitive. As early as April 1971, just two months after Faggin had produced a complete working chip set, Busicom management approached Intel with a request to renegotiate the contract. Faggin recommended to Intel President Noyce that Intel renegotiate, giving price concessions in exchange for abrogation of the exclusivity clause. Hoff made a similar request:

> I talked to marketing people who were going to Japan. ... Our marketing people did not seem terribly enthused [when I asked them to negotiate for those rights] but they did indeed negotiate for those rights, and they came back in May with the right[s].[38]

These rights came in two stages, each with a price concession to Busicom. At first, Intel had limited rights to sell the chip set as long as it was not sold to other calculator manufacturers, and later

Intel gained universal rights to sell the chip set, which it called the MCS-4 (short for Microcomputer System four-bit).[39]

Faggin disputes Hoff's role:

> I started pushing management to go into the open market with that chip. Now, Ted Hoff is saying he was the one doing it, but actually he was against it. He was telling everybody that it was only good for calculators, so I took it upon myself to show management that I could actually solve other mechanical problems using the 4004. ... When it was time to develop the production tester for the 4004, I used the 4004 as a controller ... and used that to say, "now tell me that it is only good for calculators." I built a lot of momentum inside the company to actually go market the 4004.[40]

Although Intel had gained the right to sell the microprocessor (Figs. 6 and 7), the company did not do much to exercise that right. At first, the company did not seem to recognize the potential for the microprocessor. Marketing viewed the microprocessor narrowly, as only a direct competitor to the minicomputer.

> But nothing was done [to follow up the negotiated rights to market the MCS-4], and there was a lot of negative feeling within Intel. Primarily in marketing. One marketing guy said, "the total sales of minicomputers is 20,000. We are latecomers to the business, so we will be lucky to get 10% [of the business]. 2,000 computers is not worth all this." The other position was that, even if we announce [the product], computers take a lot of [staff support] and we have no way [to do this]. Some of these strategies were discussed. [The argument was given that] we can hand-hold a few key customers, and the rest of them will be on their own—but a lot of people who buy minicomputers are on their own. They get a manual, and we could put together a manual ... with examples how to program it. But basically [customers] were [to be] on [their] own.[41]

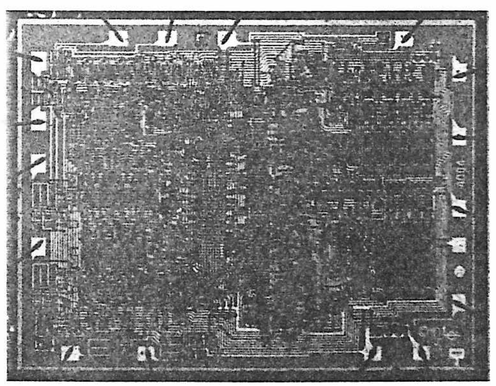

Fig. 6. The Intel 4004 microprocessor.

The senior management was no more certain than the marketing department of the value of the new product. Hoff remembers having a meeting with Noyce and others. Hoff said, "They had a tiger by the tail and did not know how to handle it. They were just reluctant to make a decision."[42] Noyce and Hoff indicate that this uncertainty was paralleled in Intel's board of directors:

> There was debate, though, as to whether Intel should exercise its new option. Some members of the board of directors were not certain the company should venture into the systems business. In the end, the view of Arthur Rock, chairman of the board, prevailed and the board endorsed the venture.[43]

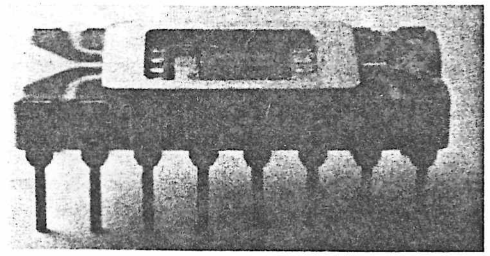

Fig. 7. The Intel 4004 in its package.

Photo courtesy of Intel.

The change took place at about the time when Intel hired a new marketing director, Ed Gelbach. He had previously been at Texas Instruments, which had shown an interest in logic devices. In fact, work by Gary Boone and others on a microprocessor was already under way at Texas Instruments when Gelbach joined Intel. Gelbach swept away the concerns formerly expressed by marketing and helped push Intel into the microprocessor business. One of the most compelling arguments inside the company at that time was that customers would need memory devices to attach to the microprocessor, so the microprocessor was regarded as a way of enhancing the market for Intel's primary business interest.

In the 15 Nov. 1971 issue of the trade journal *Electronic News*, Intel ran a large advertisement, "Announcing a new era of integrated electronics." At the Fall Joint Computer Conference held in Las Vegas, Nevada, that same month, Intel staffed a suite where it distributed information about the MCS-4. "Customers came in and really inundated them, [wanting to know] what is this computer on a chip thing."[44] Intel received 5,000 responses to the *Electronic News* announcement, far greater response than to any previous product announcement. In 1971, Hoff and Mazor went on the road in the United States and Faggin in Europe, giving talks about the MCS-4. Hoff remembers standing-room-only crowds and on many occasions having to relocate these meetings to larger lecture rooms.

Certainly by the end of 1971, Intel marketing and senior management recognized the value of the new product. By late 1972, the technical press was taking notice, and companies such as National Semiconductor and Rockwell were beginning to build their own microprocessors. By the mid-1970s, the business media were paying attention to the microprocessor, led by a major article in 1975 in *Fortune*.[45] By the end of the decade, public interest had been captured.

Faggin has pointed out that marketing a microprocessor is more difficult than marketing conventional electronic components. In order to market the microprocessor, Intel had to produce not only the data sheets giving the product's specifications but also "a programming manual, application notes showing how to use the components, a development board capable of implementing a functional prototype of the hardware, and a cross-assembler (i.e., a program running on a minicomputer that enabled the conversion from instruction mnemonics into machine language)."[46] Most difficult of all, one had to teach applications engineers to change their approach to design, to seek software rather than hardware solutions. For a while, Intel spent more on printing and mailing manuals (trying to interest applications engineers) than it gained in revenue from microprocessor sales.[47] The company was able to turn this marketing difficulty into a business opportunity, however, by developing design tools, such as prototyping boards and software assembler and simulators, which it sold to applications developers. In the first few years, these design tools were more profitable than the sale of the microprocessors themselves.

The difficulty of teaching application engineers to program rather than hardwire their logic functions was compounded by the limited capabilities of the 4004 microprocessor. The application to the calculator was obvious, but for what else was the 4004 appropriate? The answer, Intel decided, was embedded control, and Intel set about to create a market, concentrating first in business machines, aviation and medical applications, and test equipment.[48] For example, the 4004 was placed in test equipment so that engineers would not burn out their equipment by setting the dials incorrectly. Intel also saw opportunities for using microprocessors as controllers in durable consumer goods such as washing machines and microwave ovens. The company solicited applications suggestions from its customers, including one who told them of attaching microprocessors to cows to monitor water and salt consumption and milk production.[49]

Conclusions

Intel has had an impressive history as both technical innovator and profitable business, and it has every right to be proud of its role in the development of the microprocessor. However, several claims that seem to have become accepted lore in the engineering community do not hold up under historical scrutiny. One is that Intel invented the microprocessor. If one means by this statement that the company was the first to conceive of the microprocessor and introduce the concept to industry, then it is quite clear that this claim is false. The stored-program computer, which was used prominently as a calculator in the 1950s and 1960s, was one of the most lauded achievements of the postwar era and was familiar to every engineer working in the semiconductor industry. That industry itself had the computer as its most prominent application area. With the scale of integration on chips doubling every year, by the 1960s the technology was reaching a point where it was technically feasible to build a central processing unit on a chip. We have seen, not surprisingly, that a number of different groups independently came to Hoff's concept of a computer on a chip.

It is clear that what was important in the "invention" of the microprocessor was not the conceptualization but rather the implementation of an economically sound product. On these grounds, Intel has a stronger claim. It was the first company to successfully build and commercialize a microprocessor product. It recognized an application where it made both technical and economic sense to use a microprocessor, and it carried forward the project successfully. But it must also be remembered that Busicom provided the application, the funding to carry out the development, and the stimulus to Intel to complete the project after the funding had been supplied. The behind-the-scenes role of Sharp as technological entrepreneur—a fact that was completely unknown to the other principles—should also be remembered. (In fact, Sasaki also provided start-up funding to Faggin when he founded the rival microprocessor firm Zilog.)[50]

For a while, Intel spent more on printing and mailing manuals (trying to interest applications engineers) than it gained in revenue from microprocessor sales.

A second piece of lore that merits historical reinterpretation is Intel's foresight in developing the microprocessor. The evidence indicates that the Busicom project was attractive to Intel not because of the important new technology the project would develop, but primarily because it was a cash cow that would enable the company to continue its operations while it pursued its principal interest in semiconductor computer memories. Even after the MCS-4 chip set had been successfully completed, the company did not at first fully recognize the potential of microprocessors. Marketing reaction ranged from unenthusiastic to hostile, senior management was indecisive in promoting the technology, and the technical people had only an inkling of the range of applications for which microprocessors might be used. It took no more than a year for these initial positions to change, but it was only with its third microprocessor project, the 8080, that Intel made sufficient commitment to this field to invest its own money in development.

A third piece of common lore is to assign the invention of the microprocessor solely to Hoff. This is intended in no way to disparage Hoff, a truly remarkable engineer. But it must be remembered that Hoff's contribution was primarily to have one good idea about how to reconceptualize an existing project, making economical use of the microprocessor, and then to work for a short period of time to flesh out the architectural design—without completing it. Much of the hard work in logic design, chip layout and fabrication, and customization to application were accomplished by Shima and Faggin with little, if any, of Hoff's assistance. Faggin remembers that Hoff seemed to have lost interest in the Busicom project after he moved on to the 8008 project and that there was little contact with Hoff as Faggin worked feverishly to make the chip set a reality.

There may be many reasons why Hoff has been given so much credit for the microprocessor. People need to have heroes and simple stories to tell and remember, and a sole inventive genius conforms to this need. Western culture appreciates scientific feats more than engineering ones, so it is not surprising that greater credit is awarded to conceptualization than to implementation. It has also been suggested that Intel's powerful public relations machine has done little to disabuse the notion that people who remain close to the company (Hoff) deserve more credit than others who moved on to rival firms (Faggin)—although it is beyond the scope of this paper to evaluate this claim.[51]

It is difficult to apportion credit fairly to the other principal participants in this story. This has been a contentious issue for many years, and Faggin, Hoff, and Shima have decidedly dif-

ferent viewpoints about this matter.[52] A lot of the controversy may be explained by the different interests and backgrounds of the actors, which led them to have different sets of priorities and values.

It is clear that Faggin rescued the Busicom project and worked long and hard to make it a success. He seems to have made major contributions to the architectural, logical, and circuit designs and to have been almost single-handedly responsible for the chip layout and fabrication. Over the next several years, Faggin managed Intel's growing microprocessor business, which amounted to approximately [illegible] percent of the company's sales by 1974. He was the cofounder and chief executive officer of Zilog in 1974, which was a very important manufacturer of semiconductor devices for the early personal computer industry and a formidable competitor to Intel for a while. His entrepreneurial, managerial, and technical abilities in semiconductors have continued to show in his current start-up firm, Synaptics.

It is much more difficult to evaluate Shima's contributions. Shima has written his personal account of his role in the development of the microprocessor, in which he assigns himself a central position in the development of the 4004, 8080, Z80, and Z8000 microprocessors. However, in interviews, Sasaki, Faggin, and Hoff have strongly disputed Shima's claims.

Shima correctly claims that he was the designer of the original Busicom plan, important elements of which were incorporated into the chip set Intel built. Shima also correctly claims that Intel did not have organizational capability in logic chip design (at least until Faggin was hired) and that he provided this skill to the project at a critical time, even if his capability was of a self-taught variety. Shima was the principal conduit for the knowledge of the application, which shaped many aspects of the design. He was an important catalyst in persuading Intel to follow through on its contractual commitment to Intel, and later he played an important role in designing the chip set into a line of Busicom products—even though they were ultimately not enough to prevent Busicom from going out of business.

Shima was much in demand. Intel courted him to work on the redesign of the clunky 8008 microprocessor into the much more successful 8080 microprocessor. Faggin hired Shima away from Intel to work for Zilog, where he played a useful role in the development of the highly successful Z80 and Z8000 microprocessors.[53] Later, when he decided to return to his native country, Intel accommodated him by creating a new laboratory in Japan.

However, there is another side to the Shima story. Hoff and Faggin credit Shima with being an excellent detail man, but not with being someone who made any essential contributions to the conception or design. Faggin referred to Shima as a "supertechnician" with machine-like virtues:

> Shima is almost like a computer in the sense that he does not make mistakes. He can teach you talents. You can almost always rely on him when he says, "Yes, I am finished." You will find no mistakes in that work. He was an incredibly strong right hand. With Shima I would say to do it this way and then it would be. I would say, "check my work; here is the way I want the logic to be done. Clear the tables, do this, do that." And I would rely on him.[54]

Other people also had a role in the development of the microprocessor. Shima credits Mazor as an important go-between to Hoff, especially when Shima's English language skills were weak. Gelbach seemed to have turned around the attitude toward microprocessors in the marketing department and to have instilled some of the interest Texas Instruments had in logic devices into the memory-oriented Intel culture. The contribution of Noyce as president remains unclear, but it is apparent that he played an important background role throughout this story. In Japan, Murakami and Sasaki were important background figures. The story is most appropriately told as one of many individuals, Japanese and American, working sometimes together and other times at cross-purposes, to socially construct the microprocessor.

Acknowledgments

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[23] Shima interview.

[24] Hoff interview.

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[28] Shima interview. Faggin, 1992, p. 146, corroborates this story.

[29] Hoff interview.

[30] Most of this biographical information is taken from Faggin, 1992, and the Faggin interview.

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[32] Shima, personal communication, 10 Dec. 1994.

[33] Shima, personal communication, 10 Dec. 1994.

[34] Real, 1984, p. 12.

[35] Shima interview.

[36] Hoff interview.

[37] Faggin interview.

[38] Hoff interview.

[39] Private discussion with Hoff.

[40] Faggin interview. The author has no way of reconciling these two conflicting accounts.

[41] Hoff interview.

[42] Hoff interview.

[43] Noyce and Hoff, 1981, p. 13.

[44] Hoff interview.

[45] Bylinsky, 1975.

[46] Faggin, 1992, p. 148.

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[49] Hoff interview. The product literature in the Intel archives gives some indication of the wide applications of the 4004, including fanciful uses such as described in "Microprocessor Computes and Checks Life Cycle Tendencies in Coin-Operated 'Biorhythm' Machine," 20 Oct. 1975, p. 5. Technical publications regularly described how to use the 4004, e.g., R.H. Cushman, "What Can You Do With a Microprocessor?" *EDN*, pp. 42-47, 20 Mar. 1974; Cushman, "How to Get Acquainted With a μP", *EDN*, pp. 46-51, 20 Sept. 1974; B. Cole, "4-Bit Controller System Upgraded," *Electronics*, pp. 167-168, 14 Nov. 1974; L.J. Mandell, "Pitfalls to Avoid in Applying μP's," *EDN*, pp. 22-26, 20 Jan. 1975.

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William Aspray is executive director of the Computing Research Association. His earlier positions included faculty posts at Williams College and Harvard University, associate director of the Charles Babbage Institute, and director of the IEEE Center for the History of Electrical Engineering. His historical writings on computing include *John von Neumann and the Origins of Modern Computing* (MIT Press, 1990) and (with Martin Campbell-Kelly) *Computer: A History of the Information Machine* (Basic Books, 1996). He is presently writing a history of the academic discipline of computer science and engineering in the United States to 1980.

The author can be contacted at
Computing Research Association
1875 Connecticut Avenue NW, Suite 718
Washington, DC 20009, U.S.A.
(202) 234-2111
e-mail: aspray@cra.org